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WATER, ICE, STEAM – HOW CHANGES IN QUANTITY LEAD TO CHANGES IN QUALITY

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People have been boiling water for several thousand years. This simple activity happens every day, billions of times over, on every continent in the world. It is one of the real foundation activities of human society. The science behind this simple act reveals much about how the world works, and, how we can learn to change it.

Consider a piece of ice at a temperature of -50°C in a closed container with a thermometer to measure the temperature. The container is put on the stove to heat. The temperature climbs slowly until it reaches 0°C (32°F) - the freezing point of water, or equally, the melting point of ice. This is the temperature where water changes its state of matter from solid to liquid. Scientists call this point a phase-change.

Here the temperature stops increasing. Even though heat is continually added, all the heat goes into melting the ice. When all the ice is melted, the temperature begins to climb again until it reaches 100°C (212°F). Once again, the temperature stops climbing. All the heat goes into turning the water to steam, again changing its state at another phase-point. Once all the water is vaporized, the temperature begins to increase again, due to the fact that the container is closed and the pressure increases. (A steam burn is more damaging than even a burn from boiling water because the steam has a higher temperature). Theoretically the temperature can now increase until the water molecule breaks apart, but there are no more changes of state.

Thus at certain points - the phase points - the simple quantitative increase in energy, the steady flow of heat, leads to a rapid qualitative leap, a change of state.

At both of water's phase points, something else quite interesting takes place. We expect that the temperature will keep increasing as long as the heat is applied. This makes sense: the greater the time that the heat is on the pot, the more heat is transferred into the water and so its temperature should increase. But at the phase points no matter how high the flames, no matter how long they are on the pot, no matter how much heat is applied, nothing happens to the temperature. What's going on?

The answer to this question reveals something fundamental about the change from quantity to quality. Clearly something different happens at the phase points; suddenly something new takes place. In fact, the leap from quantity to quality requires the introduction of something new. Dialectics is the concrete analysis of concrete conditions. It is very difficult to see how motion behaves dialectically in general. A very specific examination of the process is necessary to see the real interaction of dialectical laws. To understand "what is new" we must look at the nature of matter, heat, temperature and the water molecule.

HEAT AND TEMPERATURE

Everything that moves has kinetic energy, the energy of motion. Atoms and molecules have kinetic energy because they are always moving. Thus every single thing, even a mountain or stuffed fish mounted on the wall, is always in motion at the molecular level. The faster a molecule moves, the greater its kinetic energy. Heat is a measure of the total quantity of kinetic energy - the total amount of vibrations, jiggles, and pushings of all the molecules in a body. Absolute zero (-273°C) - the coldest anything can get - is the point at which virtually all molecular motion ceases. Atoms, however, still move and vibrate even at this temperature.

Temperature is the intensity of heat, or the rate of movement, due to the average kinetic energy of molecules. Heat and temperature are related, but they are not the same. A thermometer records temperature but not heat. Someone swimming in Lake Michigan has a higher temperature than the water, but the lake has much more heat, since it has vastly more molecules in its vastly greater volume. A ga-zillion molecules vibrating at 55°F together have more motion, more kinetic energy, that the mere trillions of molecules in the swimmer that stay at body temperature - 98.6°F (37°C).

Heat transfer means that vibration passes from a warmer to a cooler object until their temperatures are the same. An ice cube cools a drink by absorbing heat from the liquid as it melts. It does not add "coolness" to the drink. So as the temperature rises in the container above, the molecules vibrate faster. The energy (heat) that is transferred into the water increases the kinetic energy of the molecules, which is read as temperature.

At the phase points - the point where the leap occurs - the energy no longer goes into making the molecule as a whole move faster. The energy goes into breaking the bonds between the molecules. These bonds define the nature of ice, water or steam, and herein, lies the "something new" that drives the qualitative change.

HYDROGEN BONDS

The formula for a water molecule is H2O - meaning that one oxygen atom bonds to two hydrogen atoms. These two regions of the molecule have a slight positive charge. The outer ring of the oxygen atom has four negatively charged electrons which pair together and seek to bond to positively charged atoms like hydrogen.

Thus the water atom is polar, meaning that it has a slight electrical charge. As you can see in the picture, it is a four-cornered molecule with two positively charged "corners" and two negatively charged ones.

When one of these charged regions comes close to an oppositely charged region of another water molecule, the force of attraction between them forms a bond called "a hydrogen bond". The negatively charged "corner" of one water molecule bonds to the hydrogen atom at the positively charged "corner" of another water molecule. In liquid water this bond is relatively weak and lasts about one hundred billionth of a second.

When one water molecule bonds with another water molecule, the second molecule develops a slightly stronger charge and immediately snatches another hydrogen atom from a third water molecule, and so on. This is what gives water its character as a liquid.

When water is frozen into its solid form, each molecule forms hydrogen bonds with four other water molecules because the molecules are moving so slowly. The shape of the water molecule means that molecules with four bonds push each other further apart than they are in water. The hydrogen bonds of a water molecule are strongest at wider angles than usual for atomic bonds. This creates an open-structured crystal arrangement, pushing the atoms further apart. Thus ice is less dense than liquid water and floats on top.

This fact is critical for life on earth. Unlike water, in most substances the molecules are most dense when they are solids. If this were true for water, lakes would freeze from the bottom up, rather than from the top down. Ice accumulating on the bottom would never melt and the lake would eventually freeze solid, destroying all life.

Let's re-examine the closed container example. As heat is added, beginning at
-50°C, the energy mostly goes to moving the molecules that are held by their four hydrogen bonds. The molecules gain kinetic energy and begin to jiggle and twist. As the temperature approaches 0°C the vibrating molecules begin to break some of the hydrogen bonds.

Ordinarily one calorie of heat is necessary to raise one gram of liquid water by 1 degree Celsius. However at 0°C it takes 80 calories of heat to raise 1 gram up to 1°C! Most of this heat goes to break the hydrogen bonds, eventually allowing the molecules to start zipping around, no longer held in place by their bonds. This makes water behave like a liquid, making and breaking hydrogen bonds constantly.

What is new here is that the heat energy now becomes applied to breaking the hydrogen bonds, a necessary step before the molecules can move around in a new way. (This is an interesting metaphor for us, since the addition of new ideas first goes to break the old conceptual bonds that lock us in place, freezing our political motion!!)

Now in the liquid state, the water molecules are free to move faster. With their greater kinetic energy they are now moving too fast to form all four bonds. The molecules start bouncing off each other like tiny billiard balls. As the temperature (or the kinetic energy) increases some molecules gain so much velocity from these collisions that they can no longer form any hydrogen bonds. Then they vaporize: they leap up out of the liquid and go sailing off as single molecules in a new, gaseous state.

If you leave water in a pot at room temperature it will gradually all vaporize into the air, leaving the pot empty and dry. As water starts to boil (approaching 100°C in temperature), you can see little bubbles of vapor form on the bottom where the water is closest to the fire. These bubbles of gaseous water, or steam, rise to the surface and erupt into the air. More and larger bubbles form until the entire surface of the liquid is rolling. At this temperature, the water changes state and leaps from a liquid into a gaseous form.

At this point it takes 540 calories to turn a single gram of water into steam! Once again the temperature of the water isn't increasing because all the energy goes into breaking the last remaining hydrogen bonds that restrain the water molecules and confine them in a liquid state. Up to the 100°C phase point, the kinetic energy of the heat increased the motion of the water molecules. At that point, the molecules cannot increase their motion (which requires moving in a new way, as a gas) until all the hydrogen bonds are broken. Thus all the energy goes into breaking the hydrogen bonds, allowing a leap to take place.

Though the science in this example is complicated, the system is basically simple. In fact it is so simple that you could reverse the process by cooling the environment of the container. To turn steam into a gram of water, it is necessary to withdraw 540 calories of heat. Then the temperature will start dropping.

DEVELOPMENT

Most things in nature and social life, however, are not reversible. They develop. Their development takes on evolutionary or historical characteristics. Development passes through definite quantitative stages in one direction until the process leaps into a new qualitative situation. The US, for example, will never go back to its pre-911 life. Giant assembly-line factories are a thing of the past. No one can put Humpty Dumpty - or any broken egg - back together again. A flower will turn into a fruit or a nut, but this process is irreversible. Irreversibility is characteristic of complex processes - where development is driven by the interaction and interpenetration of many dynamic factors.

The laws of dialectics hold for this kind of complex historical development, whether its an ecosystem, a child becoming a teenager or a social system. This motion is best described by revealing how quantity changes into quality. This in turn requires understanding that the leap requires something new.

The earth is 70% water. Again we can look at water's historical behavior for a simple example. Sunshine is most intense near the equator. Here water vaporizes most rapidly from the sea, rising into the air and condensing into clouds. These clouds are carried by the prevailing winds in all directions. Many clouds cover thousands of square miles. Although they appear to "float in the air" they really weigh hundreds of thousands of tons! All that water has to come from somewhere! Clouds have a historical character, develop through stages, and reach the point of the leap. Suddenly something happens and they start to release their water as condensation - as rain.

For the leap to occur, something new must be added. It is impossible for rain to condense unless there is some tiny particle for the condensation to occur around. These particles can be smoke, dust and even pollen. The introduction of the particles cause a leap in the behavior of the cloud and it starts to rain. The great Atlantic Ocean storms called hurricanes depend on thousands of tons of dust blown westward from the Sahara Desert in Africa to provide the nuclei particles for the rain drops.

Rainfall doesn't depend on the simple numerical growth of the cloud - the number of water molecules vaporized. A cloud passes through definite quantitative stages of development, marked by changes in temperature, pressure and density in its environment. Finally all the factors have reached the critical point. Then and only then does the introduction of dust - "something new" - cause the leap to take place.

The dialectics of the leap can also be seen in the simple act of cooking. In the 1700s scientists began to develop the theory of atoms based on experiments with substances of all kinds. They found a substance in all living things that acted differently from all other substances. If an organic fluid like blood or an egg was heated, it did not become a boiling liquid like water or oil. Strangely enough it became a solid, and once it changed, it could never be reversed back into being a liquid. Scientists realized that this substance (or substances) was the basis of all life, so they called it "protein" which means "of first importance".

Proteins are organic chemicals that actively do things for the cell like carry oxygen in or permit sugar to enter. We know of thousands of proteins in the human body and many more are yet to be discovered. Proteins are formed of chains of amino acids, often thousands of units long. There are only 20 amino acids, but they can fit into the chain in any order. When we digest food, our body metabolism breaks the proteins down into their amino acid components. Then the amino acids are absorbed into our cells and used to build new proteins.

Proteins work because they have a very specific three dimensional shape that can fit only one specific molecule. In a way they are filters that catch only molecule out of the billions that are floating around inside the cell.

The three dimensional shape of the protein is everything. This shape develops by leaps from the chain of amino acids, called the primary structure. The secondary structure results from the tendency of the atoms of the amino acids to attract each other. This process is similar to what goes on with liquid water, but forms stable hydrogen bonds. This bonding causes the protein to twist and fold itself into its three dimensional shape, known as the tertiary structure. Functional proteins often have two or more chains intertwined to make its quaternary structure.

The hydrogen bonds, as well as a few others, provide the leap that turns the chain into a specific three dimensional shape. They are what give proteins their irreversible, developmental character. Proteins - and therefore life on earth - can maintain these bonds only within a tiny range of temperature, or vibrations. If the temperature goes much over 90°F we begin to feel very uncomfortable. Likewise if it falls below 50°F we feel increasingly uncomfortable.

The reason that a high fever can be deadly is that the hydrogen bonds cannot maintain themselves at this temperature. The proteins unfold and lose their special shape. Then they can no longer provide their essential function and your cells start to shut down. The same process happens with an egg you are cooking. As the heat flows into the pan the molecules get more kinetic energy and begin to move faster. Suddenly the hydrogen bonds are broken and the leap takes place. The proteins in the gooey egg unfold and then begin to solidify.

The leap is characterized by the introduction of something new. In this case it is the destruction of the hydrogen bonds that causes a rapid change in shape of the protein and this leads to completely different behavior.

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